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The financial viability of artificial drying of forest chips, a case study from Northern Finland

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ABSTRACT

The generation of energy from biomass has a relevant role in current international strategies to mitigate climate change. Particularly forest biomass is considered to be one of the leading renewable energy sources in European Union (EU) in the next few decades. Thus, every innovative solution contributing towards meeting the long-term renewable targets is called for. This study tackled a new approach: artificial drying of forest chips by applying the reserve heat from district-heating loop. We focused on estimating the effect of using an artificial drying system in a container on the financial incentives of heat entrepreneurs. Traditional forest fuel supply chain was compared to a fast forest fuel supply chain in which artificial drying was applied. In this study a heat entrepreneur is financially responsible for all the costs related to both forest fuel supply chains. A break-even price for energy used for artificial drying was determined so that the fast forest fuel supply chain would equal the traditional forest fuel supply chain in monetary terms, i.e. profitability. The case study covered seven end-use facilities located in Northern Finland and presenting an entity of app. 13–14 Gigawatt hours, GWh produced *per annum*. The results of financial analysis indicated that artificial drying of forest chips is financially viable for the heat entrepreneur if the productivity of the container exceeds ca. 3.6 dried bulk-m^3 hour^{-1}, given the observed moisture content (before and after artificial drying) in test runs. However, the results were considerably sensitive to the energy price of delivered stem chips (euros per Megawatt hour, € MWh^{-1}). Furthermore, new technical solutions to increase the productivity of the container are welcomed since at the current productivity level (range from 2.5 to 3.6 bulk-m^3 hour^{-1}) artificial drying is barely financially attractive for a heat entrepreneur.

1. Introduction

Biomass represents approximately 14% of the world's energy consumption, and biomass can be converted into bioenergy to mitigate climate change (Xu et al., 2018). The substitution of fossil fuels with renewable energy sources – such as biomass – is one of the key measures globally to limit energy related greenhouse gas, GHG emissions (Girones et al., 2017). Further, the development and utilization of biomass energy can help to change the ways of energy production and consumption (Mao et al., 2018). At global scale, however, the policies contributing renewable energy sources (incl. biomass) vary from applied directives in the United Kingdom and European Union to state- or national-level renewable energy initiatives applied in the United States (Kim et al., 2018). It has been estimated that by the year 2050, approximately 18% of the world's primary energy consumption can be satisfied by woody biomass from forest and agriculture sectors (Lauri et al., 2014).

The European Union (EU) has committed to produce 20% of their energy from renewable sources by 2020 and 27% by 2030 (European Commission, 2014). Particularly, woody biomass from forests is seen to be the key renewable energy source to help countries meet their long-term renewable energy targets (Ghaffariyan et al., 2017). In Finland the proportion of renewable energy is set to be increased up to as high as 38% of the total energy consumption by 2020 (Commission of the European Communities, 2008), and this goal had actually been already reached in 2014 (Official Statistics of Finland, 2016). This 38% goal is mainly reached

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by increasing the use of various biomasses, especially forest chips and forest industry by-products in energy generation (and also the new goal of renewables (50%) is mainly based on forest chips and industry by-products (Huttunen, 2017).

Woody biomass has competing purposes – besides the traditional and massive pulp and paper industry (Tong et al., 2018) wood can be processed in various ways to produce energy, chemicals or even food (Falck et al., 2013). Pyrolysis is an effective technique to convert biomass into easy-to-use forms of energy – such as biochar, liquid bio-oil and combustible gas (Chen et al., 2018). Biochar has various uses: heat and power generation, gas and water purification, metallurgy, soil amendment and sequestrate carbon (Weber and Quicker, 2018). Recently fast pyrolysis has been applied to produce bio-oil: an advantage of the bio-oil originates from its flexibility to be either combusted or to be upgraded into transportation fuels and commodity chemicals (Luo et al., 2017). Another method, namely the thermal degradation of lignins from woody biomass has also attracted increasing research attention, mainly because of lignin's wide variety of valuable products such as modified phenolic resins (Huang et al., 2018). Then, a relatively new and environment-friendly pre-treatment method to improve solubility of wood is mild autohydrolysis in which hemicelluloses are extracted and further chemically modified to e.g polymeric hemicelluloses which have wide application in the food industry (Deb et al., 2016). In general, hemicelluloses (such as xylooligosaccharides, XOS) are a promising extract of lignocellulosic biomass to be used as ingredients in food, animal feeds and pharmaceutical preparations (Rajagopalan et al., 2017).

Despite the vast potential of alternative uses of wood, in a small scale and decentralized operating environment (typical to sparsely populated areas – such as Finland) energy production from biomass feedstock is a relevant option (Natarajan et al., 2012) abreast with pulp and paper (Lodenius et al., 2009). With regard to energy production from biomass waste heat plays an essential role by reducing the energy costs related to artificial drying. However, potential waste heat sources are usually located at the proximity of heating plants which narrows the number of locations suitable for artificial drying. More importantly, the waste (reserve) heat sources are accessible only during off-season since at the season their full capacity is used to provide energy for district heating.

In a traditional forest fuel supply chain forest energy procurement from young thinning stands in Finland is mainly based on mechanized cutting of small-diameter trees (Routa et al., 2013), particularly in northern Finland (Repola et al., 2014). Commonly the trees are harvested as delimbed (e.g. Ghaffariyan et al., 2017) – as is the case in this paper. Having logged the delimbed stems they are usually seasonally stored outdoors in piles near to or at logging sites in order to reduce moisture content (Laitila et al., 2017). Then, the delimbed stems are comminuted at the landing (roadside), at the terminal or at the plant (Laitila and Väätäinen, 2012). Finally, the stem chips are further transported to the heating (or power) plant, either directly or via an intermediate storage near to or at the heating plant, i.e. end-use-facility. A representative traditional forest fuel supply chain from young thinning stands is presented in Fig. 1. In the fast forest fuel supply chain the harvested, delimbed trees are chipped fresh, app. from 1 to 4 weeks after harvesting. Then the fresh stem chips are artificially dried in a container in order to reduce moisture content. A typical fast forest fuel supply chain considerably shortens the time of the supply chain compared to the time period of the traditional supply chain (Fig. 1).

A recent review article (Ghaffariyan et al., 2017) emphasizes the importance of increasing energy efficiency in the forest energy supply chain through reduced moisture content. When comparing the traditional and fast forest fuel supply chains, the main interest is on the possible advantages of artificial drying over natural drying outdoors. In general, there are two main advantages associated with artificial drying over natural drying in piles outdoors, namely *i)* predictability and *ii)* a minimal risk of insect infections. The former (*i*) originates from the fact that in artificial drying environment (temperature and duration) can be fully controlled whereas in natural drying weather conditions are unpredictable (Wolfsmayr and Rauch, 2014), although natural drying is most efficient during the spring and summer (Routa et al., 2015). Then, natural drying during summer increases the risk of insect infection (such as bark beetle infestation) particular in coniferous stands (Kanzian et al., 2016). Further, natural drying is related to a relatively long time period: it takes several months to achieve low enough moisture content. This further creates two separate problems: biodegradation leads to loss of dry matter and more importantly, loss of energy rich extractives (Routa et al., 2017). In addition, storing in outdoors binds a considerable amount of capital (Rauch, 2010). On the other hand, artificial drying introduces additional processes and costs to the supply chain (Wolfsmayr and Rauch, 2014).

Since bioenergy supply chain design plays a crucial role in improving economic competitiveness of biomass feedstocks (Paulo et al., 2015), we illustrate a design in which fresh forest chips are artificially dried resulting in an increase to energy efficiency of the supply chain. Furthermore, the artificial drying is conducted by utilizing existing hot water circulating in a district heating loop during off-season, which covers on average months from May to September/October in northern Finland (six to seven months). This would improve the financial viability of the artificial heating because additional heat sources are not required. The main hypotheses to be tested are: 1) there is a certain threshold value for maximum heating costs in artificial drying, and 2) values below that maximum point would warrant financial incentives for a heat entrepreneur to apply artificial heating system within the forest fuel supply chain.

The rest of the paper contains the following parts. The calculation framework and methodology as well as the case study are presented in section 2. Section 3 presents the results of the paper and in section 4 the results are discussed and conclusions are drawn.

2. Material and methods

2.1. Financial framework and analysis

A heat entrepreneur applying artificial drying has to cover the costs involved with installation of the container (incl. investment costs for piping and heat exchanger), operating costs (incl. electricity, labor and heating for artificial drying) as well as a rent of the container (this is based on the operating days *per annum*). In this analysis, all the above-mentioned costs involved with using the container for artificial drying are summed up and expressed as a lump sum cost against the produced energy (heat), € MWh^{-1} at the end-use-facility. Technically, the analysis is conducted by comparing in detail the two above-mentioned supply chains (traditional forest fuel supply chain and fast forest fuel supply chain including artificial drying), and further assessing the heating cost in artificial drying to break-even with traditional forest fuel supply chain. First, net benefit for quantity of stem chips Q_i at heating plant entity (consisting of several separate heating plants – see the next paragraph below for details) is assessed according to the traditional forest fuel supply chain:

$$NB_i^{TRAD} = Q_i * E_i^{TRAD} * \overline{\omega} - \left[\sum_{k=1}^{K} (dml_k + cap_k) + \sum_{n=1}^{N} tc_n + fh_l + cc_l \right] \quad [1]$$

where NB_i^{TRAD} = net benefit of the traditional supply chain for

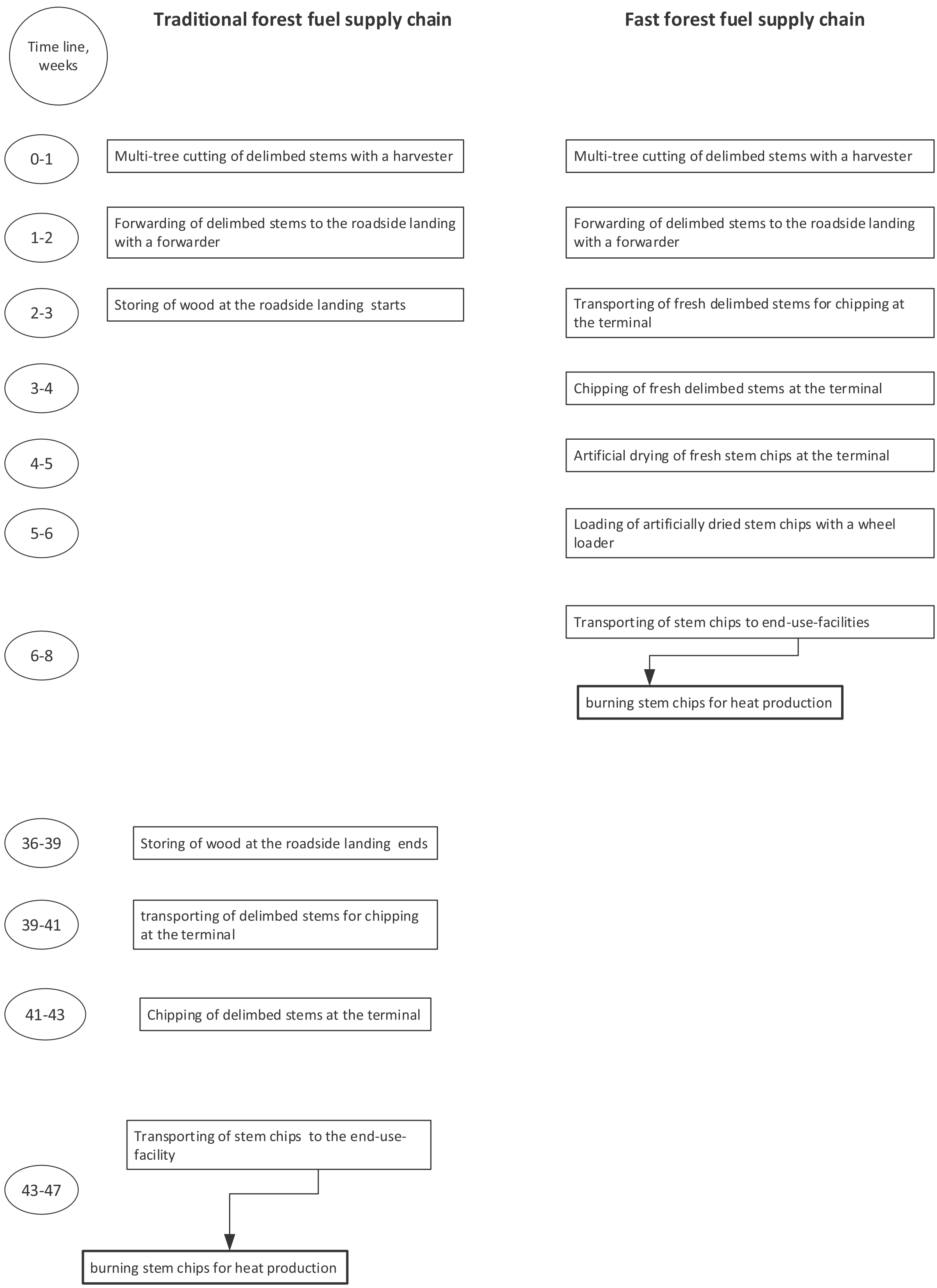

Fig. 1. A schematic on different work stages related to traditional and fast forest fuel supply chain. Time line is directive, not absolute.

quantity Q_i of stem chips delivered to all heating plants within the entity, €, Q_i = total quantity of stem chips, bulk-m^3, E_i^{TRAD} = average chip energy intensity for Q_i in traditional forest fuel supply chain, MWh bulk-m^{-3}, ϖ = unit energy price, a fixed market value regardless of the supply chain (€ MWh^{-1}), dml_k = dry matter loss per month in storage k, € (Note that a storage can consist of either delimbed stems or stem chips), cap_k = capital cost associated with storage k (a compounding discount rate was applied resulting in a cost presented in Table 1) €, tc_n = transportation costs associated with work stage n in the traditional supply chain, € (Note that both

stem chips and delimbed stems are transported in this supply chain), fh_I = forest haulage cost of the amount I of delimbed stems, € (The amount I of delimbed stems corresponds to total quantity Q_i of stem chips by conversion coefficient presented in Laitila et al., 2017) and cc_I = cutting cost of the amount of I of delimbed stems, €. For simplicity, dry matter losses and capital costs are included into the analysis only if the duration (of storage k) exceeds or is equal to one month. Since the total time horizon in assessing the net benefit, NB_{ji}^{TRAD} is less than or equal to a calendar year, discounting the right-hand side terms is irrelevant (see Price, 2018). Then, we applied a value for euro (€) according to international exchange rates, dated 10th July 2018.

The net benefit for quantity of stem chips Q_i at heating plant entity according to the fast forest fuel supply chain is calculated:

$$NB_i^{FAST} = Q_i * E_i^{FAST} * \varpi - \left[\sum_{k=1}^{K} (dml_k + cap_k) + \sum_{n=1}^{N} tc_n + \sum_{s=1}^{S} dc_s + fh_I + cc_I \right] \quad [2]$$

where NB_i^{FAST} = net benefit of the fast forest fuel supply chain for total quantity Q_i of stem chips delivered to all heating plants within the entity, €, Q_i = total quantity of stem chips, bulk-m^3, E_i^{FAST} = average chip energy intensity for Q_i, MWh bulk-m^{-3} (Note that $E_i^{FAST} > E_i^{TRAD}$), ϖ = unit energy price, a fixed market value regardless of the supply chain (€ MWh^{-1}), dml_k = dry matter loss per month in storage k, € (Note that here the storage consists solely of stem chips), cap_k = capital cost associated with storage k (€), tc_n = transportation costs associated with stage n in the fast supply chain, € (Note that both delimbed trees and stem chips are transported also in the fast forest fuel supply chain), dc_s = cost associated with operation s in artificial drying (Note that also the rent of the container is included into this term, since rent depends on the operating days *per annum*), €, fh_I = forest haulage cost of the amount I of delimbed trees, € and cc_I = cutting cost of the amount of I of delimbed stems, €. Also for the fast forest fuel supply chain discounting is neglected in the analysis.

In order that NB_{ji}^{FAST} to equal NB_{ji}^{TRAD} we first need to isolate the term $\sum_{s=1}^{S} dc_s$. Then, as mentioned above, we treat the term as a lump sum, and we solve $NB_{ji}^{FAST} = NB_{ji}^{TRAD}$ without the term $\sum_{s=1}^{S} dc_s$. This allows us to calculate the maximum value for $\sum_{s=1}^{S} dc_s$. Next, we subtracted the sum of s, …, S from the maximum value of $\sum_{s=1}^{S} dc_s$ so that only the heating cost in artificial drying is left out, i.e. an unknown value. Finally, we assessed the unknown value by applying computational iteration which was here carried out using Solver tool embedded in Microsoft Excel. The nonlinear generalized reduced gradient method (GRG2) was applied as the solving method (Microsoft Office, 2010). Furthermore, the unknown value (representing the break-even heating cost in artificial drying) was determined for the case study entity consisting of seven end-use-facilities (described in detail in the next paragraph). Technically, the break-even heating cost in artificial drying (€ MWh^{-1}) is presented against the different productivity levels of the container. These different productivity levels are based on recent empirical test runs of the container (2.5 and 3.6 bulk-m^3 hour^{-1}), and on alternative levels (5, 7.5 and 10 bulk-m^3 hour^{-1}) assuming further technological improvement of the container.

2.2. The case in northern Finland

The case study included seven (7) end-use-facilities, i.e. heating plants totaling of 17 000 loose-m^3 delivered stem chips corresponding of 13 311–13 923 MWh of energy, depending on the final moisture content (moisture content was set to fluctuate - see below). The end-use-facilities were located in northern Finland, covering a radius of app. 20 km, the centre being a small municipality at the proximity (ca. 25 km) of Rovaniemi, 66°N 23′ and 25°E 22’. Both the traditional and fast forest fuel supply chains took place within the above-mentioned radius and location. Technically, one of the seven end-use-facilities was chosen to be a terminal where

Table 1
Relevant cost variables with their values associated with traditional or fast forest fuel supply chain. All costs expressed as € solid-m-3.

Cost variable	Traditional	Fast
Organization cost	3.2[a)]	identical[b)]
Cutting (delimbed),	15.6	identical
Forwarding, i.e. forest haulage (delimbed)	6.8	identical
Transporting [c)]	3.7[d)]	3.78/3.94/4.85[d)]
Chipping of delimbed stems at the terminal	5.5	identical
Loading with wheel loader	1.9	identical
Delivery of chips from the terminal [e)]	1.6	identical
Stumpage price of delimbed stems	5.5	identical
Average storage duration (delimbed stems), months	9 months [f)]	1 month [g)]
Capital (interest) cost, storage of delimbed trees	1.2 [h)]	0.1 [h)]
Average storage duration (stem chips), months	0 month [h)]	2 months [i)]
Capital (interest) cost, storage of stem chips	0	0.26 [j)]

[a)] All values are based on Laitila et al., (2017).
[b)] Organization cost of the fast forest fuel supply chain is identical to that of the traditional forest fuel supply chain (i.e .3.2 € solid-m^{-3}).
[c)] Transporting conducted with a 76-tonne timber truck.
[d)] Unit transportation costs are depended on the moisture content: for traditional forest fuel supply chain 40% moisture content is applied whereas for fast forest fuel supply chain 45% (3.78), 50% (3.94) and 60% (4.85) moisture contents are assumed.
[e)] Delivery executed with a 76-tonne chip truck.
[f)] During the 9 month storing of delimbed stems a total of 6.75% dry matter loss is applied (e.g. Routa et al., 2018) generating a cost of 0.36 € m^{-3}.
[g)] In the fast forest fuel supply chain delimbed trees are stored outdoors at maximum of one month (in most cases not at all) and no dry matter losses are involved.
[h)] The absolute unit value of capital cost, of course, depends on the duration (see Laitila et al., 2017, p.7, Eq. (2)).
[i)] In the traditional forest fuel supply chain the stem chips are immediately (within 1–2 weeks) burnt for heat production whereas in the fast forest fuel supply chain the artificially dried stem chips are stored 2 months on average (a buffer stock).
[j)] The absolute unit value of capital cost depends on the duration.

both the chipping as well as artificial drying took place. Delimbed stems were transported to the terminal from different individual stands (Laitila et al., 2017), and after chipping at terminal stem chips (traditional) or artificially dried stem chips (fast) were transported to other six end-use-facilities according to the cost levels presented in Table 1. Since there are variable values (and assumptions) depended on the particular case, these case-sensitive values are next discussed and presented in Table 2. With regard to moisture content, a range of 45%–60% (before artificial drying) and 20%–40% (after) were applied (Table 2). The first empirical test runs (conducted by authors in June 2018) of the container confirm these ranges to be relevant. For the traditional forest fuel supply chain a fixed 40% moisture content (after 9 months drying outdoors) was used (Table 2). Then, for the price of stem chips, a 5-yr arithmetic average was applied (Table 2), derived from the official statistics of consumer prices of domestic fuels in energy production (Statistics Finland, 2018). Finally, two alternative assumptions on operating hours per day were made: either 16 or 20 h per day was applied in the analysis.

2.3. Sensitivity analysis

Since the energy price plays an essential role for e.g. heat entrepreneurs' business economy (Ranta et al., 2017) an alternative unit price for the fast forest fuel supply chain was applied. Namely, an additional 1 € MWh^{-1} (changing the original unit price, 21.15 into 22.15 € MWh^{-1}) was applied assuming that heating plants are willing to pay some extra for more homogenous and less-moisture raw material compared to traditional forest fuel supply chain (see e.g. Raitila and Heiskanen, 2014). There is a recent study supporting this willingness to pay more assumption (see Raitila and Heiskanen, 2015).

Table 2
Case-sensitive values and underlying assumptions relevant to study context.

Moisture content before[a)]	Moisture content after[b)]	Scenario[c)]
60%[d)]	40%	**Δ20A**
50%	30%	**Δ20B**
45%	25%	**Δ20C**
60%	35%	**Δ25A**
50%	25%	**Δ25B**
45%	20%	**Δ25C**
Prices and costs		*Unit value*
Energy price (of delivered stem chips)		21.15 € MWh^{-1}
Leasing cost (a rent) of the container[e)]		150 € day^{-1}
Electricity power[f)]		20 kW[g)]
Labor cost[h)]		20 € day^{-1}
Installation cost[i)]		2967 € year^{-1}

a) Moisture content of stem chips before artificial drying in the container.
b) Moisture content after artificial drying.
c) Abbreviations for scenarios are used hereafter for convenience (a scenario consists of a "Δ" as moisture content difference, a number as degrees in *Celsius* and a letter as an alternative).
d) Net calorific value corresponding a particular moisture content was adopted from Laitila et al., (2017).
e) The leasing costs of the container is based on 5-yr agreement, 7% interest rate and the total number of operating days (*p.a.*) of the container.
f) This includes all electricity required for mechanics inside the container and e.g. controlling the feeding of stem chips (*Note*: this does not include the energy required for artificial drying –since heating in artificial drying is calculated separately).
g) Energy power of the electricity of the container, unit price 4.1 cnt kWh^{-1} during operating hours.
h) Labor cost is based on the assumption in which on average one effective hour is required per operating day (the employee is on hold duty basis).
i) Installation costs include costs of piping and heat exchanger with the identical time horizon as for leasing costs (i.e a 5-yr agreement).

3. Results

3.1. Main analyses

The break-even heating cost in artificial drying fluctuated between 0.03 and 2.03 € MWh^{-1}, depending on the productivity of the container, operating hours per day as well as on the moisture content of stem chips before and after drying (Fig. 2a–d). In brief, the higher the break-even heating cost, the more profitable the artificial drying would be. For instance, when moisture content of stem chips before artificial drying was 60% and after 40%, the break-even heating cost in artificial drying was 0.41 € MWh^{-1} assuming a 16-h operating day and 7.5 bulk-m^3 hour^{-1} productivity of the container (Fig. 2a). Further, with 2.5 and 3.6 bulk-m^3 hour^{-1} productivity of the container and 60% moisture content before the artificial drying was unprofitable, regardless of the operating hours per day (Fig. 2a–d: negative values of the bars indicate inability to pay for any heating cost in artificial drying). When moisture content before artificial drying was 60% and after 35% (Δ25%), the break-even heating cost in artificial drying was 0.72 € MWh^{-1}, with a 20-h operating day and 5 bulk-m^3 hour^{-1} productivity of the container (Fig. 2d).

3.2. Sensitivity analysis

A price premium of 1 €MWh^{-1} had a crucial impact on the profitability of the fast forest fuel supply chain – even with a relatively low productivity level of the container (3.6 bulk-m^3 hour^{-1}) the break-even heating cost varied between 0.17 and 1.10 € MWh^{-1}, depending on the moisture content (before and after) and operating hours per day (Fig. 3b–d). However, with a 16-h operating day and the same productivity level of the container (i.e. 3.6 bulk-m^3 hour^{-1}) the fast forest fuel supply chain was unprofitable (Fig. 3a: negative bars).

4. Discussion

Since biomass supply chains are complex by nature involving a number of operational factors and quality aspects (Sosa et al., 2015), there are also several possibilities to reduce the supply chain costs starting from bioenergy supply chain design (Marques et al., 2018) up to using new 76-tonne truck-trailers lowering transportation costs (Laitila et al., 2016). According to a recent review (Ghaffariyan et al., 2017) one of the most crucial element, however, is to increase energy efficiency in the supply chain through reduced moisture content (Zamora-Cristales et al., 2017) and dry matter losses (Routa et al., 2018). This study tackled with artificial drying of forest chips (to reduce moisture content) by determining whether there would be enough financial incentives for a heat entrepreneur to apply artificial drying as a part of a (fast) forest fuel supply chain. To our knowledge this study is one of the few attempts (see Le Lostec et al., 2008; Raitila and Heiskanen, 2014, 2015) to assess the financial viability of artificial drying of wood chips in a context covering an operational real-life case: seven end-use-facilities, a heat entrepreneur and a container for artificial drying especially designed for the purpose. Prior to concluding, however, some constraints, assumptions and a critical view on our results with respect to existing literature and prevailing conditions need to be addressed.

First, this study does not present any detailed thermodynamic model (incl. exergy analysis) related to the artificial drying in the container (cf. Wang et al., 2016). Rather, the study scope was to assess whether there are financial incentives involved in artificial drying of forest chips from the practical (operational) point of view, without modeling the energy and exergy balances (Terehovics et al., 2017). Then, with regard to potential waste energy sources

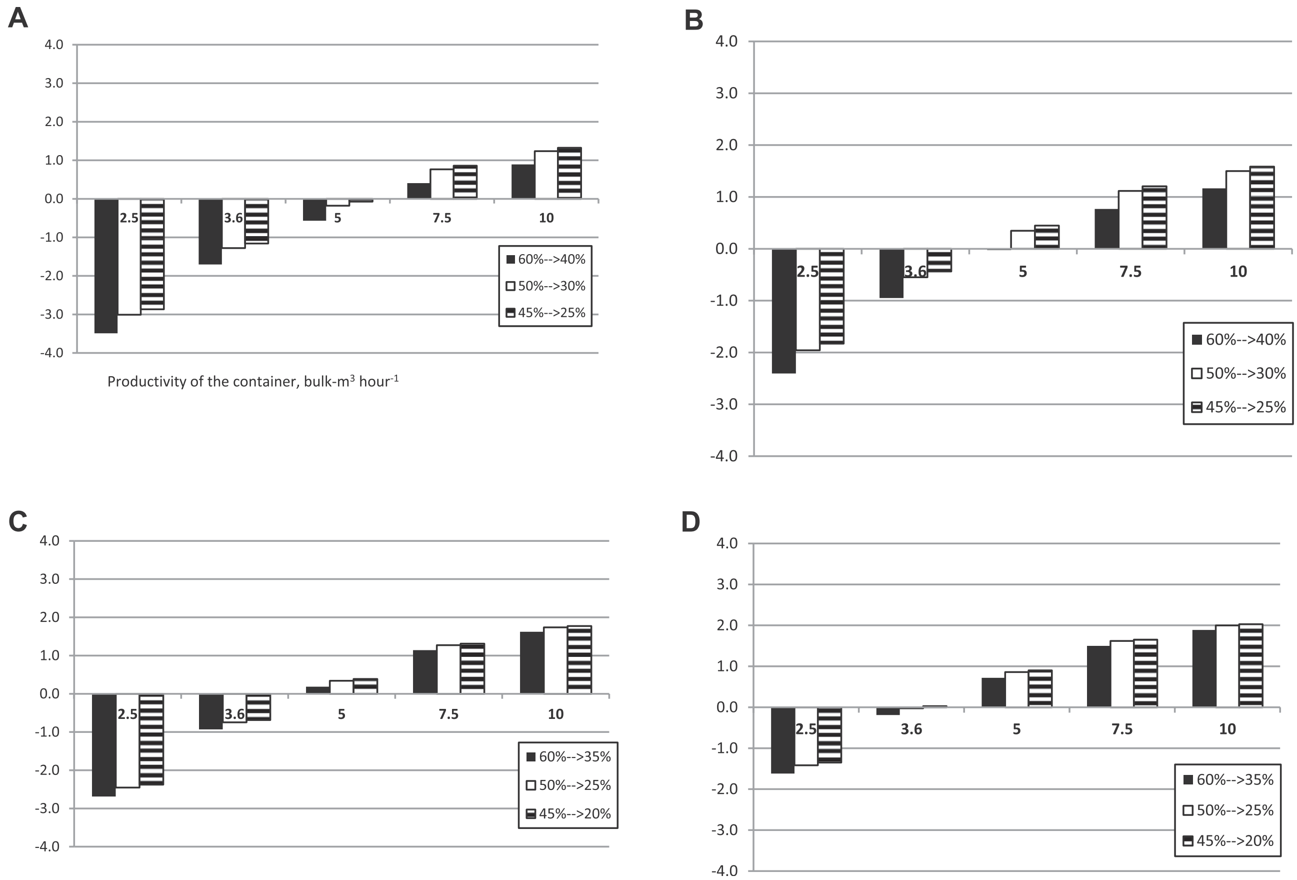

Fig. 2. a) Break-even heating cost (€ MWh-1) associated with a 16-h operating day, alternative moisture contents before and after artificial drying (Δ20%: 60%→40%, 50%→30% and 45%→25%) and various productivity levels of the container: 2.5, 3.6, 5, 7.5 and 10 bulk-m3 hour-1, b) break-even heating cost associated with a 20-h operating day, other variables as in graph a), € MWh-1, c) break-even heating cost (€ MWh-1) associated with a 16-h operating day, alternative moisture contents before and after artificial drying (Δ25%: 60%→35%, 50%-→25% and 45%→20%) and various productivity levels of the container: 2.5, 3.6, 5, 7.5 and 10 bulk-m3 hour-1, d) break-even heating cost associated with a 20-h operating day, other variables as in graph c), € MWh-1.

we chose waste heat from district heating since in the case study the district-heating loop was connected to the end-use facility, and the artificial drying in a container took place at the end-use facility, i.e. heating plant. In Finland, the market share of district heating companies (incl. cooperatives) is as high as 46%, and about half of the population in Finland utilizes district heating (Paiho and Saastamoinen, 2018). Further, wood covered ca. 26% of the production in district heating (Paiho and Saastamoinen, 2018), and heating plants using biomass feedstock are widely scattered in Finland (Karhunen at al., 2015). Thus, integrating waste heat system into district-heating loop for artificial drying would be feasible to carry out even at large scale, given that the actual process would be financially attractive for heat entrepreneurs. There are, of course, other waste energy sources such as biogas from farms (Hengeveld et al., 2016) and energy recovery from wastewater treatment plants (Piergrossi et al., 2018), or using low-cost biochar applications (Li et al., 2018) or even utilizing seasonal heat storages (Moser et al., 2018). Further, a relatively new method is to apply charcoal additive into e.g. agricultural fermentation residue, and generate cost-efficiently energy which can further be used for instance for artificial drying of forest chips (Marousek et al., 2015). At the current level of development regarding alternative waste energy sources or heat sources in general, the most promising might be biogas from farms (Hengeveld et al., 2016). This is due to two distinctive facts: first, farms (applying manure fermentation) are sparsely located as heating plants are, and second regional biogas grids (collecting biogas from several digesters) are already on the way (Hengeveld et al., 2016). The latter enables connecting the container of artificial drying directly into the biogas grid. However, the national subsidy policy related to solid biofuels plays an important role in waste heat production – the applied policy might even prevent the use of a particular biofuel as a waste heat source, as the Czech case has shown (Mardoyan and Braun, 2015).

The main results demonstrated that with today's productivity levels of the container (observed productivity between 2.5 and 3.6 bulk-m^3 hour^{-1}) the fast forest fuel supply chain is unprofitable from the entrepreneur's point of view. Stated differently, the artificial drying does not pay off resulting in a negative financial outcome, *ceteris paribus*. Thus, some technological improvement is called for in order to provide financial incentives for heat entrepreneurs to engage with artificial drying of stem chips. However, the results were utmost sensitive to the applied sale price of stem chips: with a 1 € MWh^{-1} sale price premium (compared to traditional supply chain) the fast supply chain and thus the artificial drying became financially attractive for a heat entrepreneur, even with a relatively low productivity level of the container. A bigger issue would be whether the end-use facilities are actually willing to pay more for (less-moisture and more homogeneous) stem chips produced through the fast supply chain, rather than through the traditional supply chain (cf. Raitila and Heiskanen, 2015). The 1 € MWh^{-1} sale premium applies particularly for small-scale combined heat and power plants (roughly, size < 20 MWe; see Salomón

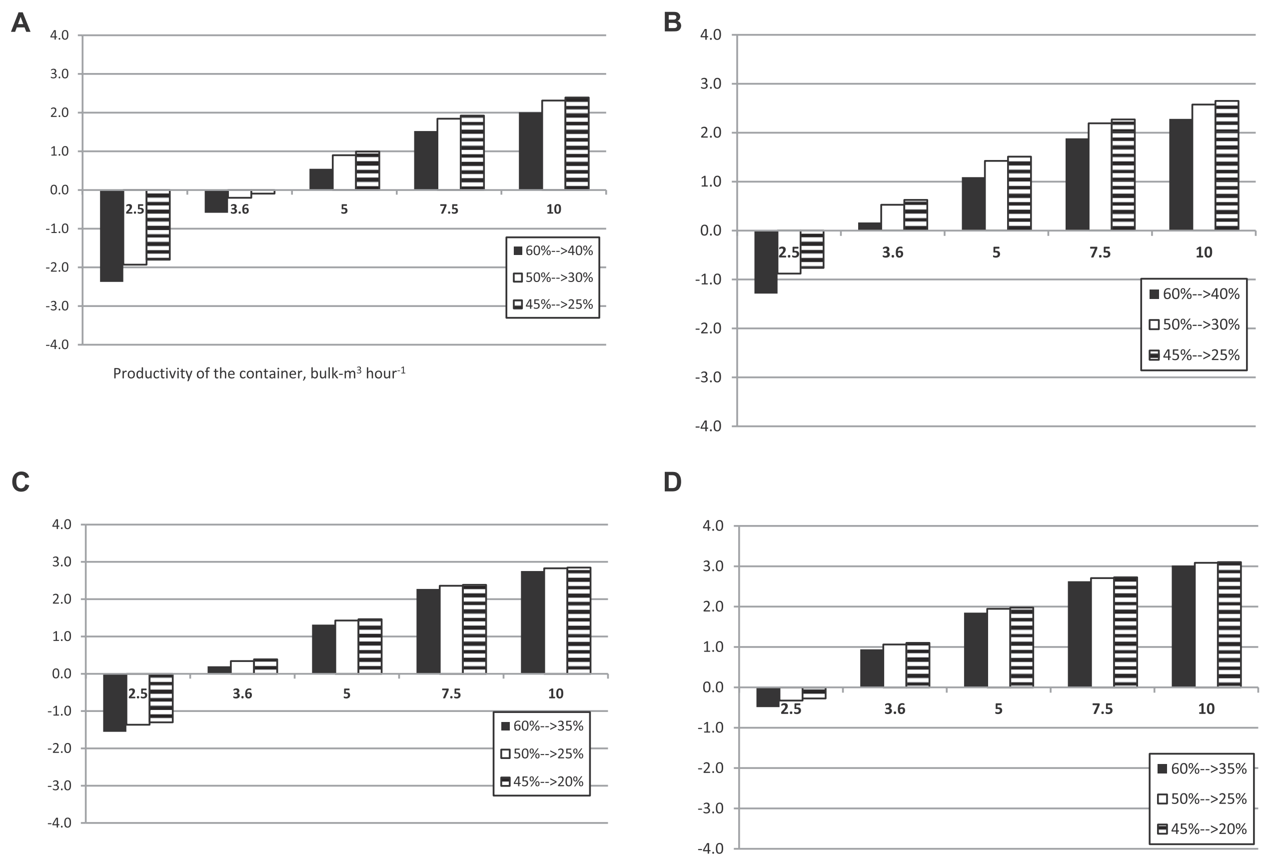

Fig. 3. Sensitivity analysis: a 1 € MWh-1 sale price premium for the fast forest fuel supply chain. a) Break-even heating cost (€ MWh-1) associated with a 16-h operating day, alternative moisture contents before and after artificial drying (Δ20%: 60%–>40%, 50%–>30% and 45%–>25%) and various productivity levels of the container: 2.5, 3.6, 5, 7.5 and 10 bulk-m3 hour-1, b) break-even heating cost (€ MWh-1) associated with a 20-h operating day, other variables as in graph a), c) break-even heating cost (€ MWh-1) associated with a 16-h operating day, alternative moisture contents before and after artificial drying (Δ25: 60%–>35%, 50%–>25% and 45%–>20%) and various productivity levels of the container: 2.5, 3.6, 5, 7.5 and 10 bulk-m3 hour-1, d) break-even heating cost (€ MWh-1) associated with a 20-h operating day, other variables as in graph c).

et al., 2011) since low moisture content is essential for operating efficiency in combined heat and power, CHP plants (e.g. Sermyagina et al., 2016). As a curiosity it should be stressed out that each fossil fuel (incl. peat) has a specific emission factor, but wood is held as renewable and its factor is 0 (Ranta et al., 2017).

Finally, one particular interesting way to improve the productivity of the artificial drying in a container is to decrease drying air humidity ratio of air before drying since the drying air with smaller humidity ratio content is able to attract more moisture from the drying of forest chips (Terehovics et al., 2017). Such decrease calls for new innovative technical solutions yet to come. However, according to the law of discontinuous evolution (Samset, 1992), technical development proceeds stepwise in the case of a single job or solution, and there is always a risk that when a new method (due to technical development) is competing against existing ways of doing work, the new method is ruled out although it has the potential of becoming the most productive (Björnheden, 1997). Thus, near future will tell us whether new technical solutions will succeed in artificial drying.

4.1. Conclusions

This study demonstrated that artificial drying of forest chips would be financially attractive for a heat entrepreneur when a waste heat source is available producing energy below a current market price level. In the near future, if the productivity of the container (in which the artificial drying takes place) can technically be improved, financial viability can be achieved even with waste heat sources using market prices in energy production. This paves the way for vast opportunities in green energy business.

Declaration on interest

Declarations of interest: none.

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